SP-100 PROGRAM

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SP-100, THE U.S. SPACE NUCLEAR REACTOR POWER PROGRAM*

By: Vincent C. Truscello†

Abstract--DARPA, in conjunction with DOE's Office of Nuclear Energy, and NASA's Office of Aeronautics and Space Technology are jointly sponsoring a space nuclear reactor power system program known as the Space Power-100 (SP-100) Development Project. The program is presently in the critical technology phase. This phase, better known as technology assessment and advancement, includes mission requirements definition, system conceptual designs, and critical technology development. A ground test phase decision is scheduled for July 1985. If the decision is positive, the next phase would begin in fiscal year 1986. An overriding concern in conducting this program is to ensure that nuclear safety is being properly addressed even in these early stages.

1. Introduction

Recent and past studies have indicated that several classes of missions would be enabled or significantly enhanced by space nuclear reactor power systems, including military and civil satellite missions, manned space stations, and missions to the planets, comets, and asteroids. For systems requiring more than 25 kWe of power, the power-to-mass ratio of a nuclear reactor system can be considerably higher than that of competing solar/battery systems. The nuclear system can readily be used for deep-space applications, and it need not be oriented toward the sun. The rugged, low-cross-section configuration would enhance survival in radiation fields, reduce drag in orbit, decrease the detection cross section, and enhance maneuverability and hardenability.

A space nuclear reactor power system based on already proven technology is ready for a ground test phase now, but its performance would be limited in terms of power-to-mass ratio, total power, and life. It is likely that potential users would not find it interesting enough to employ in their missions.

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To meet this challenge, DARPA, in conjunction with DOE's Office of Nuclear Energy, and NASA's Office of Aeronautics and Space Technology have combined efforts to sponsor a space nuclear reactor power system program known as the Space Power-100 (SP-100) Development Project. Three major laboratories are collaborating in this Program: NASA's Jet Propulsion Laboratory (JPL), and Lewis Research Center (LeRC), and DOE's Los Alamos National Laboratory (LANL).

A significant portion of the SP-100 Project is aimed at identifying plausible missions, determining their requirements, and identifying space nuclear reactor systems that would be capable of meeting these requirements. These system identification activities are being closely followed by the development of enabling technology. To insure that the concepts and supporting technology will not result in system designs that introduce unacceptable risk with regard to nuclear safety, a concurrent safety evaluation program is being conducted. The remainder of this paper presents the status of the various activities in support of the SP-100 Project.

2. Mission Requirements and Analysis

Missions that are significantly enhanced or even made possible by the use of a nuclear reactor power system are of great importance to NASA, DOD, and a variety of commercial interests. Such missions need to be identified, characterized, and analyzed for their requirements on the power system design.

Broad classes of missions have been identified as shown in Figure 1. JPL and LeRC will conduct the planetary, civilian/commercial and manned space station studies through a combination of in-house and subcontract activities. LeRC/JPL will be supported by the Navy and Air Force and their contractors to conduct the military mission studies. Work in the mission analysis area has just recently begun, and the activities are still mostly in the start-up mode (see Figure 2). LeRC, for instance, has only recently engaged the Boeing Company to conduct mission analysis studies for manned space station applications. The DOD (Navy) has in place a contract with the General Electric Company to study potential military missions. Several smaller DOD contracts are expected to be in place shortly. Early in fiscal year 1984 a contract will be let by JPL to study civilian/commercial missions. NASA has also set up a top-level advisory group to help identify civilian missions for a space nuclear reactor power system.

The one area that has achieved some degree of preliminary results because of earlier work is the planetary program. Planetary missions can benefit significantly with the use of nuclear reactor power systems by enabling low-thrust propulsion. Nuclear electric propulsion (NEP) will allow higher mass payloads, faster flight time, and flexible encounter capability as compared with conventional approaches. Figure 3 gives an example of the trade-offs between flight time and payload size.

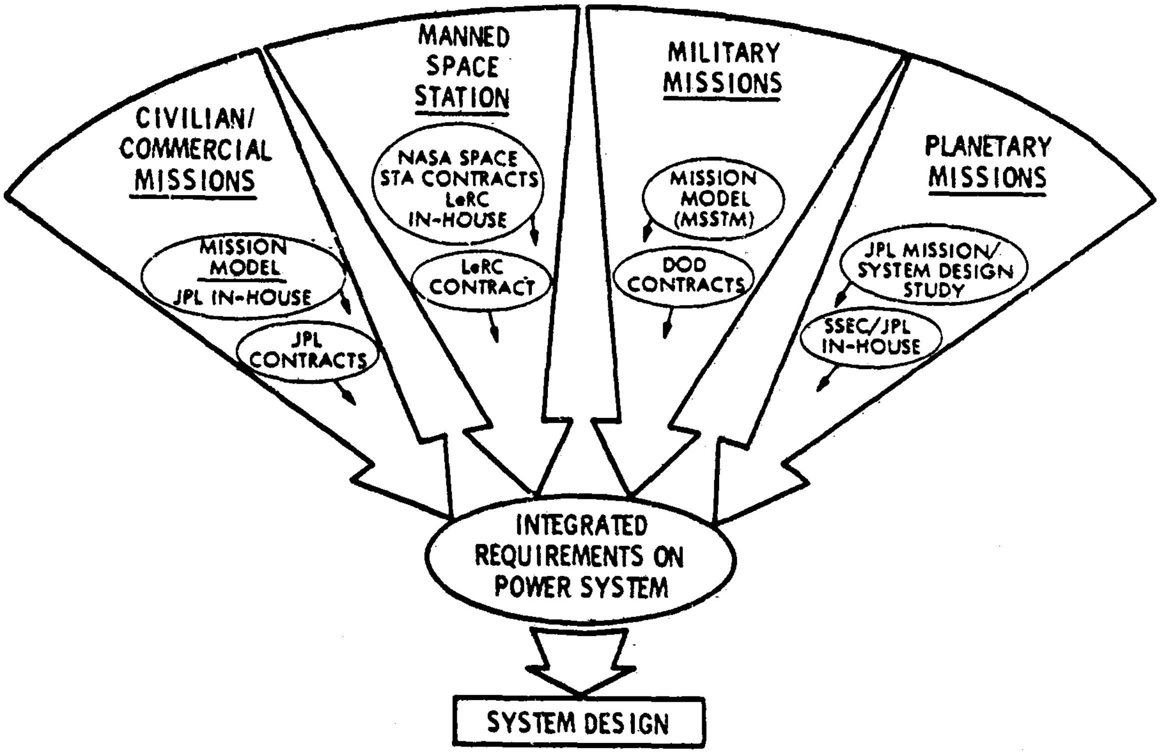

FIGURE 1 SP-100 MISSION ANALYSIS AND REQUIREMENTS

Earlier work has also defined attractive uses of nuclear power in the commercial field. Direct broadcast satellites are enhanced with the use of nuclear power by enabling the use of smaller antennas, fewer satellites, and operation during solar occultation without batteries (see Figure 4).

The mission analysis area is also responsible for developing functional requirements based on the driving factors on the system. Two editions of a design goals and requirements document have been published to date.

3. System Definition

System concepts are presently being developed for the SP-100 Project by contractors or teams of contractors, including the General Electric Company, Westinghouse Electric Corporation/Lockheed Missiles and Space Company, and ~~General Atomic~~/Martin Marietta Aerospace.

Initially the contractors reviewed and evaluated a broad spectrum of reactor and power conversion technologies (Table 1). The concepts were required to meet certain design constraints and to provide 100 kWe to the payload. Paramount constraints included a weight of less than 3000 kg, and a volume capable of being contained at launch within approximately one-third of the shuttle bay.

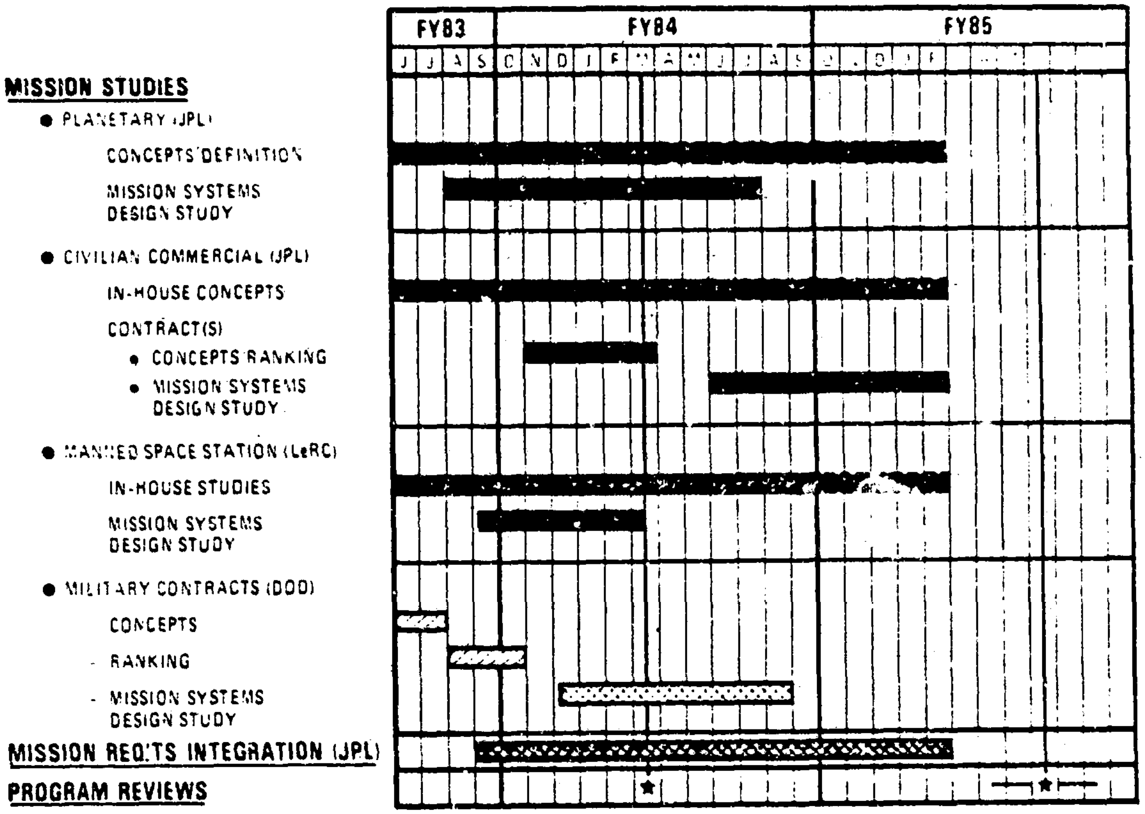

FIGURE 2 SP-100 MISSION ANALYSIS AND REQUIREMENTS PLAN

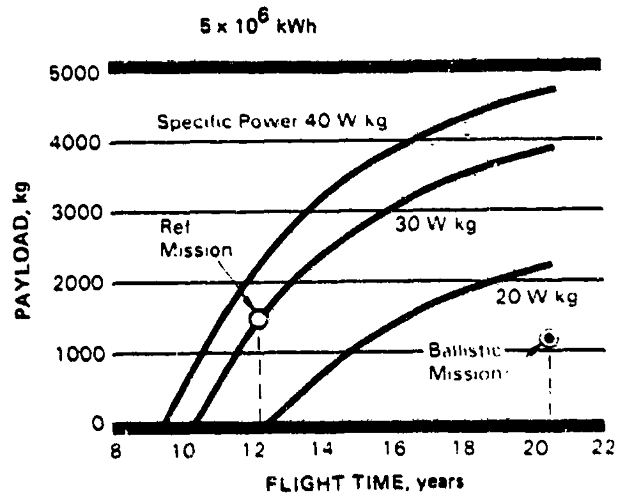

FIGURE 3 MISSION PERFORMANCE (NEPTUNE ORBITER MISSION)

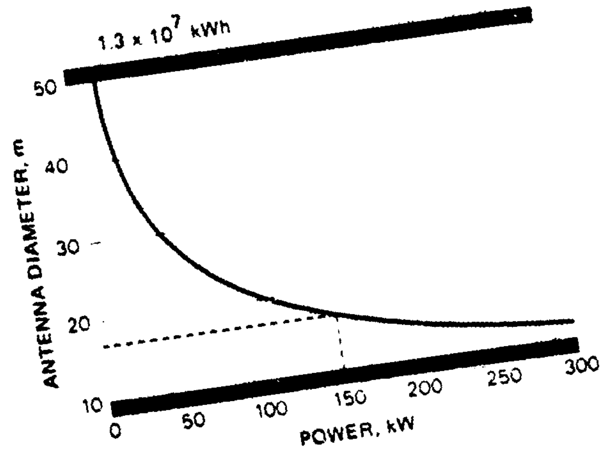

FIGURE 4 POWER VS. ANTENNA DIAMETER (ADVANCED DIRECT BROADCAST SATELLITE)

Table 1--Concepts Investigated by System Contractors

Reactor
- Fast
- Thermal
- Epithermal

Fuel
- Oxide
- Carbide
- Nitride
- Cermet
- Rod
- Pellet

Heat Transport
- Pumped liquid metal
- Heat pipes
- Pumped gas

Thermal/Electric Conversion
- Thermoelectric
- Brayton cycle
- Rankine cycle (liquid metal)
- Stirling
- Thermophotovoltaic (TPV)
- Alkali metal thermoelectric converter (AMTEC)
- Rankine cycle (organic)
- Thermionic (in-core)
- Thermionic (ex-core)

Obviously, for such a large array of potential candidates, an intensive selection process must be undertaken to define a viable system that would meet the requirements of attractive missions, yet could be developed within reasonable cost and risk. A typical configuration reviewed by the contractors is shown in Figure 5. The contractors very quickly focused on fast spectrum reactors because of weight and size constraints. In addition, early indications are that for these systems to be attractive enough for potential users, operating temperatures higher than those demonstrated to date will be necessary. For example, the large body of reactor technology data presently available from the liquid-metal-cooled fast breeder reactor will have to be expanded to enable operation of the fuel at cladding temperatures where refractory metals will be necessary (1300-1700 K). Present reactors use stainless steel materials at considerably lower temperature (900 K).

Power conversion systems also face challenging technology development issues. A substantial data base and experience already exists with space power sytems using radioisotope-fueled thermoelectric converters. Many years of actual flight experience exists but at operating temperatures of 1270 K for silicon-germanium thermoelectric materials. Temperatures approaching 1500 K and materials with improved thermoelectric characteristics may be necessary. Similarly, dynamic machines have a large data base for terrestrial applications operating at temperatures in the 850-1150 K range. Materials of construction include the super alloys. Operation at temperatures such as 1300-1600 K will require the use of refractory or even ceramic materials. The technical feasibility of fabricating components from such materials and using them in systems that have components that rotate at speeds of 50,000 rpm must be shown.

The contractors have also found that for many of these concepts to meet power requirements yet fit within the shuttle constraints will require the use of deployable waste heat radiators after deployment from the shuttle and before start-up.

The initial studies of the contractors, substantiated by independent evaluation at the laboratories, indicate that five systems are emerging as the top candidates: two static conversion configurations using thermoelectric and in-core thermionics, and three dynamic power conversion configurations using Stirling, Brayton, and Rankine engines.

Within the funding constraints, a number of these concepts will be pursued during the present technology assessment and advancement phase of the effort (1983 to 1986), to increase the probability of proving the feasibility of at least one concept. The results of this three-year phase will provide the basis to enable DOD, DOE, and NASA to decide whether to proceed, and if so with which system concept, into a ground test phase of a 100-kWe class space nuclear reactor power system.

4. Technology Development

A major part of this program is to identify what is necessary to establish proof that a particular suitable technology has reached the feasibility stage and that it is ready to enter the next and more costly phase of hardware development for the ground engineering system (GES). Not only must the feasibility issues be identified, but appropriate analytical and experimental activities must be conducted. Enough must be done during the feasibility phase to assure that the GES can be developed within acceptable risk. No major showstoppers should be expected during the GES development phase.

Major funding for technology development will, therefore, emphasize resolution of key technological uncertainties. Areas that may be addressed relate to the compatibility of refractory alloys with nuclear fuels; the effects of neutron radiation on refractory metal stability; the development of static conversion systems such as thermoelectrics capable of operating at temperatures of 1300-1500 K at suitable efficiency, weight, and lifetime; and development of dynamic conversion systems employing refractory or ceramic components.

To help determine exactly what the major technology issues are and what needs to be done to resolve these issues, an interlaboratory Technology Assessment Working Group (TAWG) was formed. The work performed by this group during March-July 1983 provided the needed insight required by the Project management to allocate resources. The decision as to how to allocate the resources had to be made prior to the availability of the final results of the system contractor downscoping activities. Fortunately, the completely independent evaluation by the TAWG provided results that were very consistent with those of the contractors taken as a whole. That is, although the individual contractor results did not necessarily agree one with the other, taken in composite, the agreement with the TAWG results was quite good.

The overall procedure used by TAWG is outlined in Figure 6. The first step was to completely characterize the various subsystems, including reactor, shield, heat transport, power conversion and processing, and waste heat radiators, in terms of weight, size, efficiency, operating temperatures, materials, etc. The information was put into system computer models illustrated schematically in Figure 7. Typical results of these system performance models were obtained as displayed in Figure 8. Charts constructed in this manner allowed ready determination of how high the operating temperature needed to be to achieve the required power (greater than 100 kWe) at a system mass of less than 3000 kg. Since temperature selection dictates the materials needed, the technology requirements were established. The chart also provided information regarding waste heat radiator area requirements and thus insight as to whether deployable radiators were necessary to meet the shuttle bay volume constraints. This chart also gave information regarding the power growth potential of each concept.

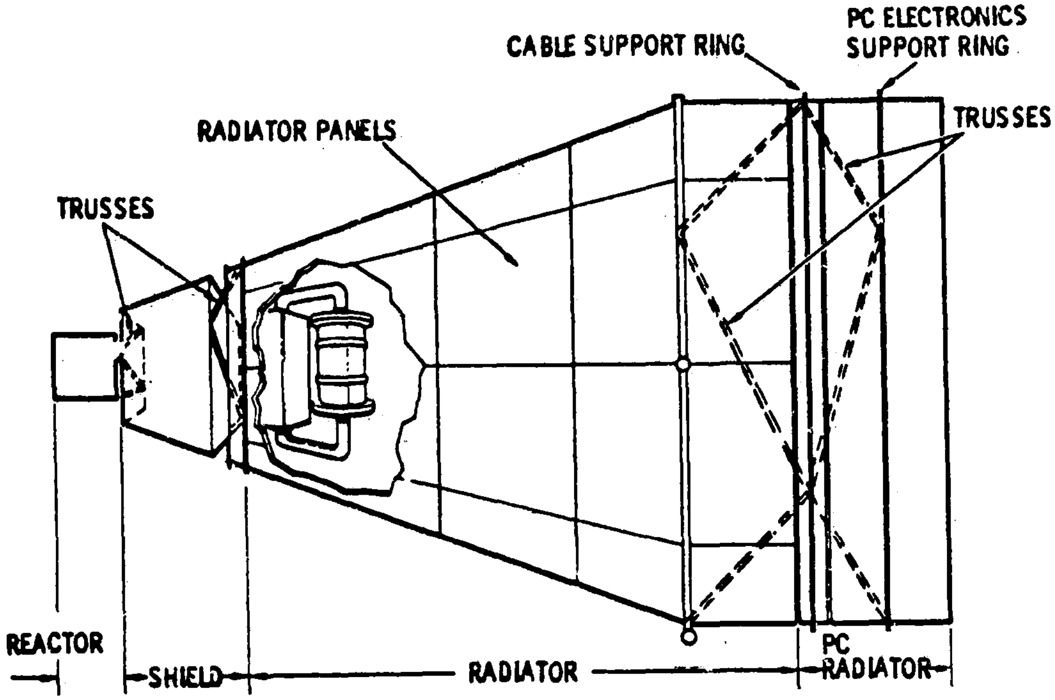

FIGURE 5 SP-100 PRELIMINARY STRUCTURAL DESIGN

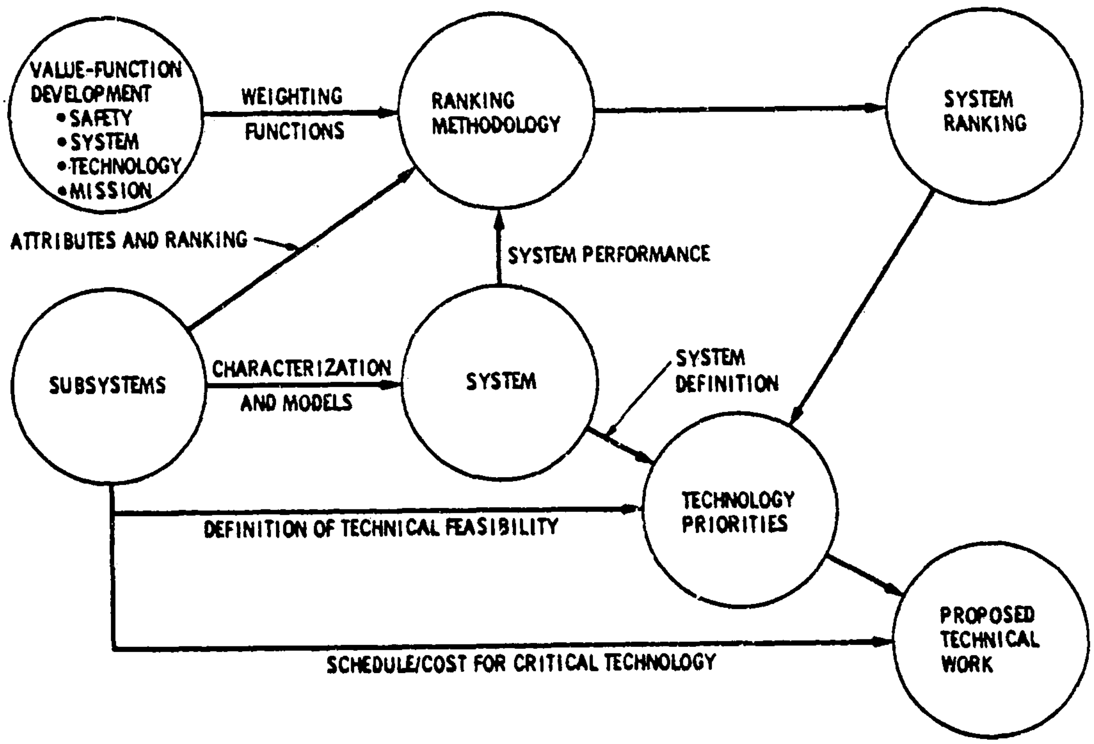

FIGURE 6 OVERVIEW OF DOWNSCOPING PROCEDURE

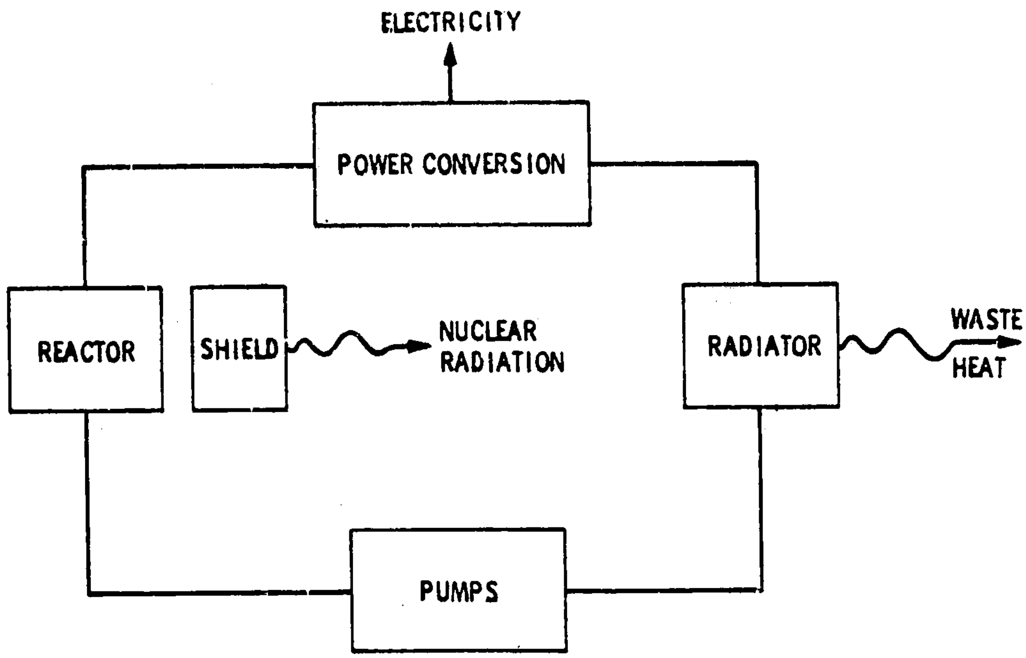

FIGURE 7 SYSTEM MODEL

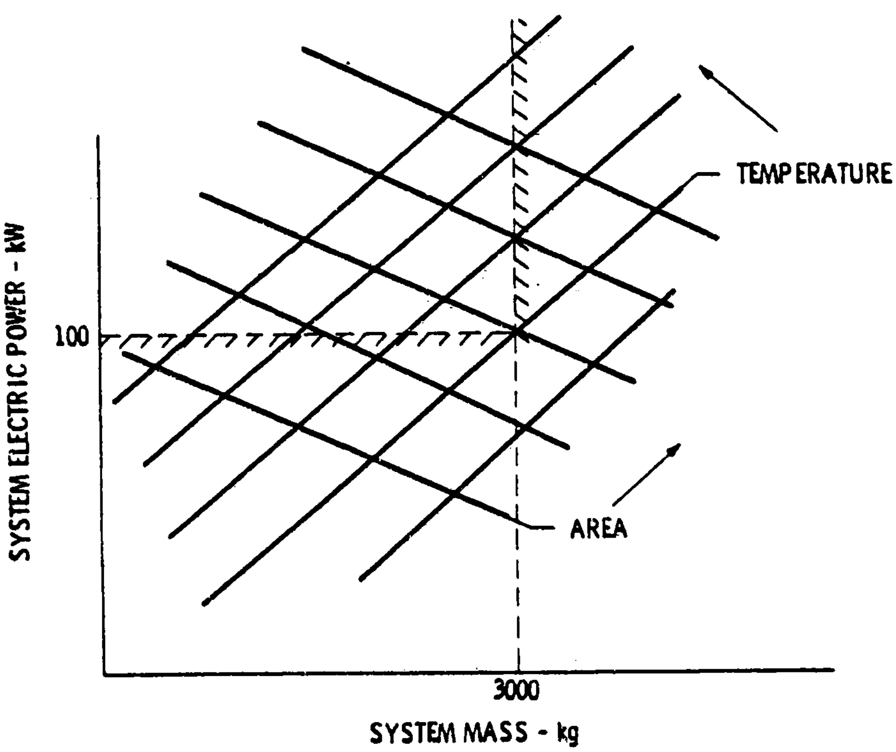

FIGURE 8 SYSTEM POWER VS. MASS

Sixteen different systems were identified capable of meeting the power and weight constraints (Table 2), each with different technology components and at different levels of technology status. The performance characteristics of these systems were provided as an input to a multi-attribute system ranking model. Other inputs to the model included a listing of the attributes and ranking of each subsystem according to each attribute. A listing of the attributes used is shown in Table 3. To establish a weighting function for each attribute, a formal process known as utility function determination was employed. In the process, a group of informed participants representing various sectors of the program (e.g., safety, system, technology, mission) were interviewed to obtain the necessary value functions. The results obtained by use of this ranking methodology are displayed in Figure 9. Certain of these systems were later rejected because they violated a second level of imposed constraint, that of maintaining a reactor core structure below a temperature of 1500 K. Systems not meeting this constraint were (1) out-of-core thermionics, (2) thermophotovoltaics, and (3) gas-cooled Brayton reactor systems. Although the alkali metal thermoelectric (AMTEC) concept was ahead of Rankine in the ranking, it was downgraded to a lower level because of the need for a technological breakthrough to achieve AMTEC electrodes that do not degrade at elevated temperatures and the opinion that such a breakthrough is quite uncertain.

Having established the five candidate systems that best meet the system constraints, the TAWG group determined the technical feasibility issues for each system and the appropriate schedule and cost to resolve these issues. Materials concerns were a major category of technological issue. Technical feasibility issues were identified in the area of materials for fuel cladding, reactor core structure, heat transport piping, heat exchangers and pumps, and power conversion high-temperature components. The major issues identified for power conversion subsystems are shown in Table 4. For reactors, the issues deal primarily with those of material concerns as summarized in Table 5.

A few of these technological issues are already under study by the Project, while most require the establishment of a development program, which is presently under way.

Table 2--Alternative System Concepts

ID Number	Power system concept	Abbreviation
1	Liquid-metal cooled/out-of-core thermionic	LOCTP
2	Liquid-metal cooled/Brayton	LBO
3	Liquid-metal cooled/Stirling	LSH
4	Liquid-metal cooled/Rankine	LRL
5	Liquid-metal cooled/AMTEC	LAP
6	Liquid-metal cooled/thermoelectric	LTEP
7	Gas-cooled reactor/Brayton	GBH
8	Heat-pipe cooled/out-of-core thermionic	HOCTP
9	Heat-pipe cooled/Brayton	HBO
10	Heat-pipe cooled/Stirling	HSH
11	Heat-pipe cooled/Rankine	HRL
12	Heat-pipe cooled/AMTEC	HAP
13	Heat-pipe cooled/thermophotovoltaic	HTPVP
14	Heat-pipe cooled/thermoelectric (1380 K)	HTEP
15	Heat-pipe cooled/thermoelectric (1250 K)	HTEPA
16	In-core-thermionic	ICT

Table 3--Attributes

- Safety
- Radiator area (m^2)
- Design reliability
- Technical maturity
- Estimated cost to reach technical readiness
- Survivability
- Producibility

Table 4--Feasibility Issues - Power Conversion

Thermoelectrics

- A material figure of merit (Z) of 1.4
- Low-weight packaging (10 kg/m^2)
- Coating to enable high-temperature operation (SiGe system only)
- Deployable radiators

Thermionics

- Fuel swelling - electrode shorting
- Electrical insulation degradation

Stirling

- Scalability
- Lifetime/endurance
- Performance with small delta T

Brayton

- Compatibility of refractory metals with system impurities
- Deployable radiators

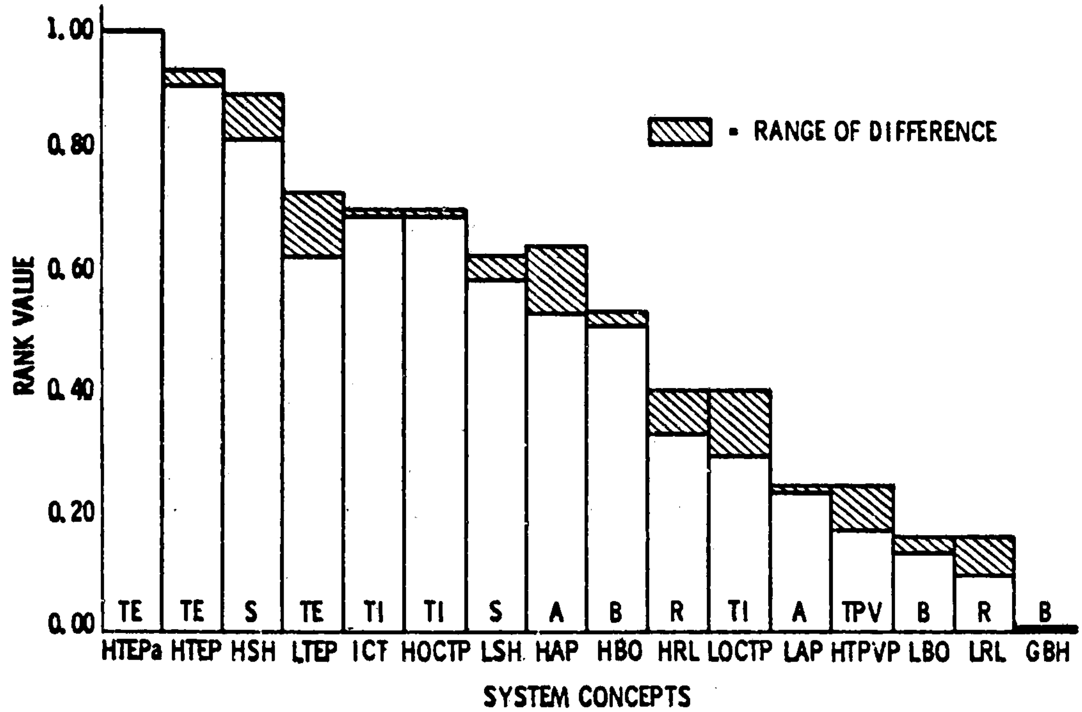

FIGURE 9 RANKING OF SYSTEMS

Table 5--Feasibility Issues - Reactor

- Chemical compatibility: fuel/clad/coolant
- Neutron irradiation behavior (swelling, property degradation)
- Refractory alloy embrittlement
- Refractory alloy workability (weldability)
- Heat pipe operation

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